

August 16, 1983

To: Larry Coulson  
From: Tim Miller *Tim*  
Subject: Jet Noise

As you know, DuPage County Airport has plans for expansion which would increase jet traffic over the Lab. Concern has been expressed that the resulting increase in noise might cause an unacceptable vibration of chamber wires and/or an unacceptable decrease in the quality of the general acoustic environment of the Lab. Bill Freeman and I have looked into this and conclude that no significant problems are expected.

The chamber wires of primary concern are those to be employed in Lab E. Their characteristics are given in Table 1. The maximum steady-state displacement of a wire driven at its fundamental resonant frequency is given by

$$Y_{\max} = 9.11 \times 10^{(\text{spl}/20)-5} a^2 \text{ cm.}$$

Where

$Y_{\max}$  = the maximum steady-state displacement (cm),

$a$  = the radius of the wire (cm), and

spl = the acoustic sound pressure level at the fundamental resonant frequency of the wire (dB).

For the 5 mil wire, the sound pressure level which causes a displacement of 4 mils is 129 dB. For the 1.2 mil wire it is 154 dB.

Audible jet passage generally takes about 15 seconds. Noise increases to a maximum at about 7.5 seconds then decreases. Based on aircraft noise data and the Lab-airport distance, the maximum effective noise levels outdoors are 85-90 dBA for the noisiest jets and 77 dBA for typical jets. The fractions of these maximum pressure levels which occur in 28-56 Hz (the octave band centered on the fundamental resonant frequency of the wires) are 65-70 dB for the noisiest jets and 55 dB for typical jets.

Levels inside buildings would be lower due to transmission

losses. Assuming a typical frequency spectrum for jet noise, the loss through 20 gauge aluminum plus one inch of fiberglass would be about 19 dB weighted over 20-20,000 Hz and about 3 dB at 40 Hz. The 40 Hz noise reaching the wires would be further reduced by 0 to 8 dB due to attenuation by the external components of the chambers. (A range is given since the components encountered by approaching acoustic waves is direction dependent.) Table 2 contains a list of sound pressure levels at various locations.

Since the sound pressure level at the wires at the fundamental resonance will be much less than 109 dB, vibration of the wires due to jet noise will not be a problem. In addition, the general quality of the acoustic environment at the Lab should not seriously deteriorate as a result of the airport expansion. Inside buildings, jet passage will generally go unnoticed. Jet noise will generally be noticeable out of doors but not annoying (77 dBA is equivalent to slightly raised speech at one meter). Peak levels of 85-90 dBA should not be a problem due to infrequent occurrence and short duration (seconds).

cc: G. Fisk  
W. Freeman  
R. Huson  
Q. Kerns  
P. Livdahl  
R. Trendler

Table 1. Chamber Wire Characteristics.

<u>Parameter</u>	<u>Sense Wires</u>	<u>Field Wires</u>
Material	Au-plated W	Au-plated W
Density	19.3 gm/cm <sup>3</sup>	19.3 gm/cm <sup>3</sup>
Length	305 cm	305 cm
Diameter	$3.05 \times 10^{-3}$ cm	$1.27 \times 10^{-2}$ cm
Tension	$8.33 \times 10^4$ dynes	$1.47 \times 10^6$ dynes
Maximum acceptable displacement	$1.02 \times 10^{-2}$ cm	$1.02 \times 10^{-2}$ cm
Mass/length	$1.41 \times 10^{-4}$ gm/cm	$2.44 \times 10^{-3}$ gm/cm
Fundamental resonant frequency	39.8 Hz	40.2 Hz

Table 2. Sound Pressure Levels at Various Locations.

<u>Location</u>	<u>Overall SPL (dBA)</u>	<u>SPL at Resonance (dB)</u>
Outside worst case	85-90	65-70
Outside typical	77	55
Inside worst case	66-71	62-67
Inside typical	58	52
Chamber worst case	N/A	54-67
Chamber typical	N/A	44-52

## Assumptions Used in the Wire Displacement Calculation

1. The acoustic pressure wavefronts are parallel to the wire axis.
2. The steady state displacement at the middle of the wire will be the maximum displacement.
3. The only resistive force is the drag force of the wire moving through air.
4. Only pressure waves near the fundamental resonant frequency of the wire will significantly displace the wire ( $f_{resonant} \approx \sqrt{2}$ ).

1.

## Maximum Steady-State Displacement of a Wire Driven at its Fundamental Resonant Frequency

$$y_{\max} = \frac{4F_0 L}{\pi^2 R} \sqrt{\epsilon / T} \quad (\text{Derivation Attached})$$

$y_{\max}$  = the maximum steady-state displacement

$F_0$  = the magnitude of the force per unit length impressed on the wire

$L$  = the length of the wire

$R$  = the frictional resistance per unit length on the wire

$\epsilon$  = the mass per unit length of the wire

$T$  = the tension on the wire

Since the fundamental resonant frequency is given by

$$f_r = \frac{1}{2L} \sqrt{T/\epsilon}$$

$$y_{\max} = \frac{2F_0}{\pi^2 f_r R}$$

2.

The Magnitude of the Force per Unit Length of a Wire Driven by Acoustic Pressure Waves in Air

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$$F_0 = 0.0074 f a^2 I^{1/2} \quad (\text{Morse, } \underline{\text{Vibration \& Sound}})$$

$F_0$  = the magnitude of the force per unit length impressed on the wire (dynes/cm)

$f$  = the frequency of the pressure waves ( $s^{-1}$ )

$a$  = the radius of the wire (cm)

$I$  = the intensity of the pressure waves (ergs /  $cm^2 \cdot s$ )

3.

## Pressure Wave Intensity from Sound Pressure Level

$$I = \frac{P^2}{\rho c}$$

$I$  = the intensity of the pressure waves  
(ergs/cm<sup>2</sup>-s)

$P$  = the rms sound pressure level (dynes/cm<sup>2</sup>)

$\rho$  = the density of air (gm/cm<sup>3</sup>)

$c$  = the speed of sound in air (cm/s)

$$SPL = 20 \log_{10} \left( \frac{P}{P_0} \right)$$

SPL = the sound pressure level (dB)

$P_0$  = the reference pressure (dynes/cm<sup>2</sup>)

$$I = \frac{P_0^2}{\rho c} 10^{SPL/10}$$

4.

## The Frictional Resistance Per Unit Length on the Wire

The frictional resistance is caused by drag when the wire moves through air.

$$F_D = C_D \rho A \frac{v^2}{2}$$

$F_D$  = the drag force (dynes)

$C_D$  = the drag coefficient (dimensionless)

$\rho$  = the density of air ( $\text{gm/cm}^3$ )

$A$  = the intercepted area ( $\text{cm}^2$ )

$v$  = the velocity of the object with respect to the fluid ( $\text{cm/s}$ )

The drag coefficient ( $C_D$ ) for an infinite cylinder may be related to its Reynolds number ( $R$ ).

The Reynolds number is given by

$$R = \frac{\rho v d}{\mu}$$

$R$  = the Reynolds number (dimensionless)

$V$  = the velocity of the object with respect to the fluid (cm/s)

$\rho$  = the density of the fluid (gm/cm<sup>3</sup>)

$\nu$  = the kinematic viscosity (cm<sup>2</sup>/s)

$d$  = a representative dimension; for a cylinder it is the diameter (cm).

The maximum Reynolds number for our wire can be calculated as follows:

$$y(t) = y_0 \cos \omega t$$

$$v(t) = \frac{dy(t)}{dt} = -y_0 \omega \sin \omega t$$

$$R_{\max} = y_0 \omega = 2\pi y_0 f_r$$

$y_0$  is the maximum acceptable displacement which is  $1.02 \times 10^{-2}$  cm (4 mils). The resonant frequency is about 40 Hz.

$$\begin{aligned} R_{\max} &= 2\pi (1.02 \times 10^{-2} \text{ cm}) (40 \text{ Hz}) \\ &= 2.56 \text{ cm/s} \end{aligned}$$

6.

The maximum Reynolds number is

$$R_{\max} = \frac{V_{\max} d}{\nu} = \frac{(2.56 \text{ cm/s})(1.27 \times 10^{-2} \text{ cm})}{(0.149 \text{ cm}^2/\text{s})}$$

$$= 0.218. \quad (\text{at } 68^\circ\text{F})$$

For Reynolds numbers less than  $\sim 5$ , the coefficient of drag for an infinite cylinder may be expressed as a power function of the Reynolds number.

Curve fit a line to the following two points:

$C_D$	$R$
100	0.051
24	0.3

$$\Rightarrow C_D = 9.10 R^{-0.805}$$

This is almost  $C_D \propto R^{-1}$ , which will turn out to be a useful result.

7.

Linearize to midpoint of range of Reynolds numbers,  $R = 0.218/2 = 0.109$ .

$$C_D = 9.10 (0.109)^{-0.805} = 54.6$$

$$C_D \approx \frac{K}{R} \Rightarrow K \approx C_D R = (54.6)(0.109) \\ = 5.95$$

$$\therefore C_D \approx \frac{5.95}{R} \quad (\text{for } R < 0.3)$$

This expression may be substituted into the expression for  $F_D$ :

$$F_D \approx \frac{5.95}{R} \rho A \frac{n^2}{2} \quad (\text{Substitute for } R) \\ = \frac{5.95 \rho A n^2}{(\frac{n^2 d}{2})(2)} \approx \frac{3 \rho v A n}{d}$$

$A$  = the intercepted area =  $dL$

$$F_D \approx \frac{3 \rho v d L n}{d} = 3 \rho v L n$$

8.

$$R = \frac{F_0}{nL} \approx \frac{3\rho v L n}{nL} = 3\rho v$$

$$R \approx 3\rho v$$

## Substitution of Coefficients Into Maximum Displacement Relationship

$$\begin{aligned}
 y_{\max} &= \frac{2 F_0}{\pi^2 f_r R} = \frac{(2)(0.0074)(f_r)(a^2)(I^{1/2})}{(\pi^2)(f_r)(3\rho\nu)} \\
 &= 5.00 \times 10^{-4} \frac{a^2 I^{1/2}}{\rho\nu} \\
 &= 5.00 \times 10^{-4} \frac{a^2 \left( \frac{P_0^2}{\rho c} 10^{SPL/10} \right)^{1/2}}{\rho\nu} \\
 &= \frac{5.00 \times 10^{-4} a^2 P_0 10^{SPL/20}}{\rho^{3/2} \nu c^{1/2}}
 \end{aligned}$$

$$P_0 = 2 \times 10^{-4} \text{ dynes/cm}^2$$

$$\rho = 1.18 \times 10^{-3} \text{ gm/cm}^3$$

$$\nu = 0.149 \text{ cm}^2/\text{s}$$

$$c = 3.32 \times 10^4 \text{ cm/s}$$

$$y_{\max} = \frac{(5.00 \times 10^{-4})(2 \times 10^{-4}) a^2 10^{SPL/20}}{(1.18 \times 10^{-3})^{3/2} (0.149) (3.32 \times 10^4)^{1/2}}$$

$$y_{\max} = 9.11 \times 10^{-5} a^2 10^{SPL/20}$$

## Sound-induced vibration of wire

Homogeneous wave egn.

$$\epsilon \frac{\partial^2 y}{\partial t^2} = T \frac{\partial^2 y}{\partial x^2} - R \frac{\partial y}{\partial t}$$

$T$  = Tension

$R$  = frict. resistance/unit length

(dynes/velocity)

$\epsilon$  = mass/unit length

$$\text{Driving force} \sim F_0 dx e^{-i\omega t} \quad F_0 = \text{force/length}$$

$$\frac{\partial^2 y}{\partial t^2} + 2K \frac{\partial y}{\partial t} - c^2 \frac{\partial^2 y}{\partial x^2} = \frac{F_0 dx}{\epsilon} e^{-i\omega t}$$

$$K = \frac{R}{2\epsilon}, \quad c^2 = \frac{T}{\epsilon}$$

Assume steady state sol'n

$$y(x,t) = \sum_n a_n \sin \frac{\pi n x}{L} e^{-i\omega t}$$

$$\frac{\partial y}{\partial t} = -i\omega \sum_n a_n \sin \frac{\pi n x}{L} e^{-i\omega t}$$

$$\frac{\partial^2 y}{\partial t^2} = -\omega^2 \sum_n a_n \sin \frac{\pi n x}{L} e^{-i\omega t}$$

$$\frac{\partial y}{\partial x} = \sum_n a_n \frac{\pi n}{L} \cos \frac{\pi n x}{L} e^{-i\omega t}$$

$$\frac{\partial^2 y}{\partial x^2} = \sum_n -a_n \frac{\pi n^2}{L^2} \sin \frac{\pi n x}{L} e^{-i\omega t}$$

Gives

$$\omega^2 \sum_n a_n \sin \frac{\pi n x}{L} - 2i\omega \sum_n a_n \sin \frac{\pi n x}{L} + \sum_n \frac{\pi n^2 c^2}{L^2} a_n \sin \frac{\pi n x}{L} = \frac{F_0 dx}{\epsilon}$$

Multiply by  $\sin \frac{\pi mx}{L}$  and integrate  $0 \rightarrow L$

$$\left[ -\omega^2 - 2ik\omega + \frac{\pi^2 m^2 c^2}{L^2} \right] \frac{1}{2} q_m = \frac{F_0}{\epsilon} \underbrace{\int_0^L \sin \frac{\pi mx}{L} dx}_{\frac{L}{\pi m} (1 - (-1)^m)} \leftarrow \begin{array}{l} \text{only odd } m's \\ \text{contribute, due} \\ \text{to symmetry.} \end{array}$$

$$\therefore q_m = \frac{-2 F_0}{\pi m \epsilon} \frac{(1 - (-1)^m)}{\omega^2 - \frac{\pi^2 m^2 c^2}{L^2} + 2ik\omega}$$

$$\text{let } \omega_m^2 = \frac{\pi^2 m^2 c^2}{L^2} - k^2$$

Then

$$q_m = \frac{-2 F_0}{\pi m \epsilon} \frac{(1 - (-1)^m)}{\omega^2 - k^2 - \omega_m^2 + 2ik\omega} = \frac{\frac{2 F_0}{\pi m \epsilon} (1 - (-1)^m)}{(\omega + ik)^2 - \omega_m^2}$$

$$q_m = \frac{\frac{2 F_0}{\pi m \epsilon} (1 - (-1)^m)}{(\omega + ik + \omega_m)(\omega + ik - \omega_m)}$$

$$\therefore y = -\frac{2 F_0}{\pi \epsilon} \sum_{m=0}^{\infty} \frac{\frac{1}{m} (1 - (-1)^m) \sin \frac{\pi mx}{L}}{(\omega + ik + \omega_m)(\omega + ik - \omega_m)} e^{-i\omega t}$$

This agrees with Morse Vibration & Sound.

Rewrite complex coeff. as ampl. and phase.

$$\frac{1}{(\omega + ik + \omega_m)(\omega + ik - \omega_m)} = \frac{1}{\omega^2 - \omega_m^2 - k^2 + i2\omega k}$$

$$= \frac{1}{\left[\left(\omega^2 - \frac{\pi^2 c^2 m^2}{L^2}\right)^2 + 4k^2\omega^2\right]^{\frac{1}{2}}} e^{i\phi_m} ; \quad \phi_m = \tan^{-1} \left[ \frac{-2k\omega}{\omega^2 - \frac{\pi^2 c^2 m^2}{L^2}} \right]$$

$$y = \frac{-2F_0}{\pi\epsilon} \sum_m \frac{\frac{1}{m}(1 - (-1)^m) \sin \frac{\pi mx}{L}}{\left[\left(\omega^2 - \frac{\pi^2 c^2 m^2}{L^2}\right)^2 + 4k^2\omega^2\right]^{\frac{1}{2}}} e^{-i(\omega t - \phi_m)}$$

at resonant freq. of fundamental mode ( $\omega = \frac{\pi c}{L}$ )

and wire mid-point ( $\frac{L}{2}$ )  $\Rightarrow \sin \frac{\pi L}{2} = 1$

$ y_1  = \frac{+2F_0}{\pi\epsilon} \cdot \frac{1}{ik\omega_1}$	$= \frac{4F_0 L}{\pi^2 R} \cdot \sqrt{\frac{\epsilon}{T}}$
----------------------------------------------------------------	------------------------------------------------------------

$m=1$  term

For sound scattering by wire (of radius  $a$ )

$$F_0 = 0.0074 f \sigma^2 \gamma^{1/2} \quad (\text{dynes/cm})$$

$\gamma$  = sound intensity ( $\frac{\text{ergs}}{\text{sec} \cdot \text{cm}^2}$ )

$$2\pi f = \omega \quad (\text{sec}^{-1})$$



Fermilab

August 19, 1983

To: Distribution  
From: Phil Livdahl *Phil*  
Subject: DUPAGE COUNTY AIRPORT EXPANSION

You have each received Tim Miller's report on jet noise effects on wire chambers. Can we convene a (hopefully last) meeting to discuss the report, its conclusions and any other thoughts we may have on this subject on August 31 at 1:30 p.m.? If this is not a possible date or time, please call Jean Plese and she will reschedule.

Thanks.

Distribution:

Russ Huson  
Gene Fisk  
Bob Trendler  
Quentin Kerns  
Larry Coulson ✓

RECEIVED

AUG 24 1983

SAFETY SECTION